Frequency Probe Measurements of Electron Density, Plasma Potential, and Electron Energy Distribution in Processing Plasmas

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ABSTRACT

RF frequency probes are an attractive alternative to Langmuir probes due to their ability to measure electron density in reactive and depositing plasma chemistries. In addition, frequency probes provide the same variety of plasma parameters for which Langmuir probes are used (plasma density, electron temperature, plasma potential and electron energy distributions). This work presents frequency probes measurements of plasma density over a range of 10^9 to 10^{11} cm^{-3} in a variety of processing plasma chemistries. This work also features high resolution energy distribution function measurements using RF frequency probes which investigate the effects of molecular gases on electron energy distributions.

INTRODUCTION

Electron beam generated plasmas are the basis for the Naval Research Laboratory's LAPPS (Large Area Plasma Processing System) program, which has been used in a variety of plasma processing efforts. Electron-beam-produced plasmas differ from conventional plasma processing sources due to the fact that ionization and excitation processes in the plasma are driven by an energetic electron beam instead of low energy discharge electrons. Electron beam generated plasmas have been shown to offer high densities (10^{10} to 10^{12} cm^{-3}), low electron temperature (< 1 eV) [1, 2, 4], low incident ion energies, and unique gas chemistries. In addition, these plasmas represent a localized, scalable plasma source that is decoupled from the vacuum chamber geometry. The system specific to this paper utilizes a steady state hollow cathode plasma electron source to produce an electron beam which is confined to a thin, large area, sheet with an axial magnetic field. This geometry produces a high-density plasma over the volume of the beam [2, 3], with decaying plasma density outside the beam volume. These unique features pose some interesting challenges in diagnosing the system. In response to these challenges NRL has developed multiple RF frequency probe geometries and measurement techniques for use as diagnostics in plasma processing systems.

RF frequency probes operate on the principles of antenna impedance in a plasma, an area that incorporates an extensive body of research going to back to the early 1960s. [5-12] RF frequency probes are of interest for any application where plasma parameters are difficult, or impossible to measure using a Langmuir probe; ion thrusters,[13] reactive processing plasmas, and depositing plasmas [14] are examples of environments where Langmuir probe measurements can be difficult due to there reliance on charge collection at the probe surface. Initially, interest in RF frequency probes grew out of a need for density measurements in harsh plasma environments; however, in addition to density, plasma potential and electron energy distribution function [15, 16, 17] measurements have also been made by adding a variable DC bias to the probes. In addition to simple antenna based RF frequency probes we also present the LCR probe [18], a variant of RF frequency probes that eliminates complications from magnetic field effects.

EXPERIMENTAL SETUP

The electron beam plasma processing chamber consists of a stainless steel, vacuum vessel situated within magnetic field coils that produce a uniform axial magnetic field within the confines of the vacuum chamber. A diagram of the experimental setup is shown in Figure 1. Within the vacuum vessel are the plasma generation and measurement components; the electron beam source, a termination anode for the electron beam, and the LCR probe and plasma frequency probe diagnostics mounted on linear motion feedthroughs. The frequency probe and LCR probe are connected via double shielded coaxial cable to a network analyzer providing a means to measure the plasma impedance characteristics.

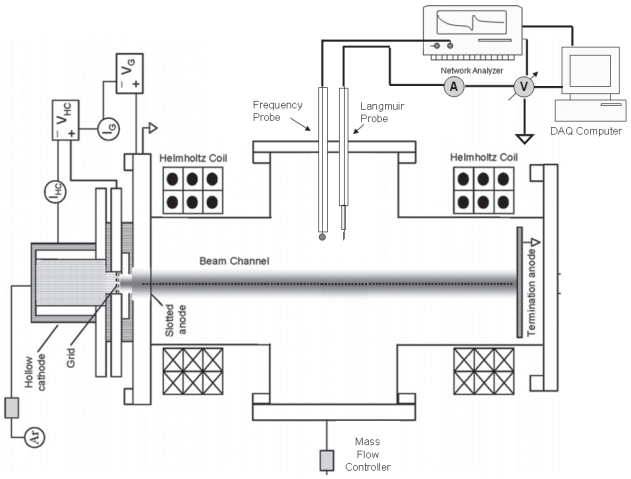

Figure 1: Diagram of the electron beam plasma processing chamber showing plasma diagnostic configuration.

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The electron source consists of a rectangular hollow cathode discharge held a few hundred volts negative with respect to an anode mesh. The anode mesh dimensions are 1 cm x 10 cm. The anode mesh is biased negatively with respect to a slotted grounded anode and serves to accelerate the electrons extracted from the hollow cathode discharge to high energy. The anode dimensions are 1 cm x 10 cm which defines the beam. The magnetic field confines the beam electrons to a sheet geometry creating a sheet - like plasma extending from anode mesh to a termination anode on the opposite end of the vacuum vessel. Further details can be found in reference [20]. For the results reported here the anode voltage was ~1 kV.

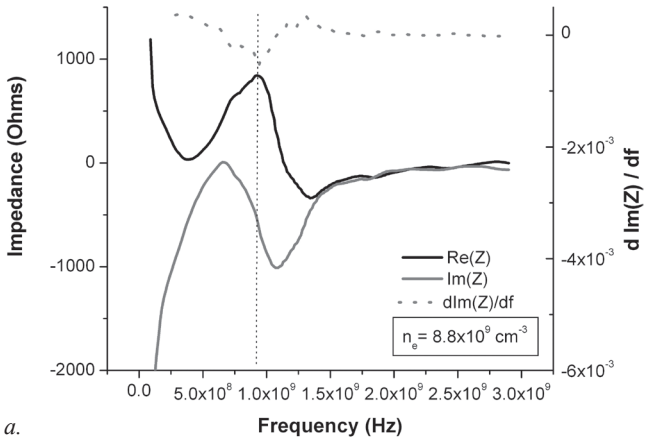
FREQUENCY PROBE OPERATION AND RESULTS

When the probes are connected to the network analyzer the complex reflection coefficient of the probes, Γ, is measured as a function of signal frequency applied by the network analyzer. This allows the probe's complex impedance, *Z*, as a function of frequency to be calculated. The presence of a plasma around the probe influences the impedance characteristics measured by the network analyzer allowing for plasma parameters to be calculated.

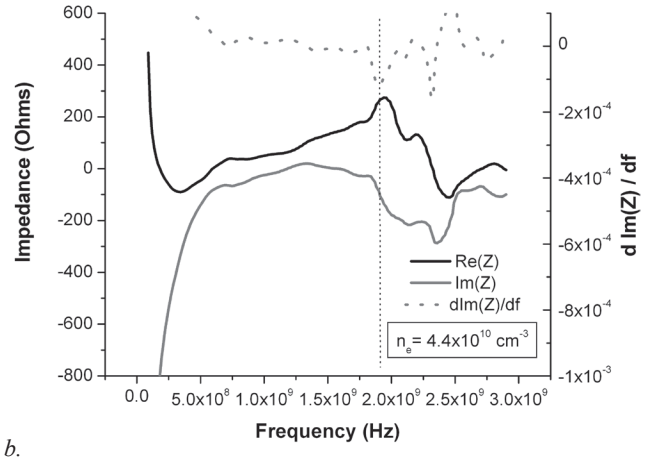
Plasma Density Measurements with RF Frequency Probes

The plasma frequency can be easily identified by investigating the characteristics of the **Re***(Z)* and the **Im***(Z)*. In the presence of a plasma a series and parallel resonance can be identified in the impedance versus frequency data. The parallel resonance, associated with a maximum in **Re**(*Z*) and an inflection point in the **Im**(*Z*), uniquely identifies the plasma frequency as has been shown in previous work [21, 22]. Once the plasma frequency is identified it is straightforward to calculate the plasma density. Figure 2 shows impedance as function frequency measurements in an oxygen plasma illustrating plasma frequency resonance. The derivative of **Im**(*Z*) is shown to assist in identifying the inflection point in **Im**(*Z*).

A shortcoming of antenna-based RF frequency probes is that they are unable to measure the plasma frequency directly when a magnetic field is present. Instead, the upper hybrid frequency is measured requiring accurate knowledge of the local magnetic structure for plasma density to be calculated [5]. The LC Resonance probe [18], or simply LCR probe, is a variant of the RF frequency probe. The LCR probe is constructed by terminating a semi-rigid coaxial cable with a small LC resonance circuit exposed to the plasma. In this work two parallel metallic plates (or mesh), one connected to the center conductor and the other to the outer shield of semi-rigid coaxial cable make up the capacitive element with the wire connections and self inductance of the parallel plates accounting for the inductive element. The resonance frequency of the LC circuit is determined by the condition where,



a.



b.

Figure 2: The Re(Z) and Im(Z) characteristics of a O_2 plasma measured (a) away from the electron beam and (b) near the electron beam by an RF frequency probe. The plasma frequency resonance is indicated on each figure by a dashed vertical line.

$$Z = i\omega L + \frac{1}{i\omega C} = 0 \tag{1}$$

and therefore

$$\omega_R = \frac{1}{\sqrt{LC}} \tag{2}$$

The introduction of a plasma around the capacitive element will alter the relative dielectric constant, $\varepsilon_p(\omega)$, defining the probe's capacitance, and thus shifting the resonance frequency. This shift in resonance frequency is related to the plasma density by the following:

$$n_e = \frac{m_e \varepsilon_0}{e^2}\left(\omega_R^2 - \omega_{R0}^2\right) \tag{3}$$

Where ω_R is the LC resonance frequency with plasma, and ω_{R0} is the LC resonance frequency without plasma present.

By tailoring ω_{R0} the LCR probe can be operated in magnetized plasmas while by-passing the complicating effects of the applied magnetic field. If the LCR probe is properly constructed, ω_{R0} can be tuned such that $\omega_{R0} >> \omega_{ce}$, where ω_{ce} is the electron-cyclotron frequency. In this case, magnetic field effects can be ignored and equation (5) can still be used to calculate the plasma density. In Figure 3, the shift in the LC resonance frequency induced by a plasma is shown.

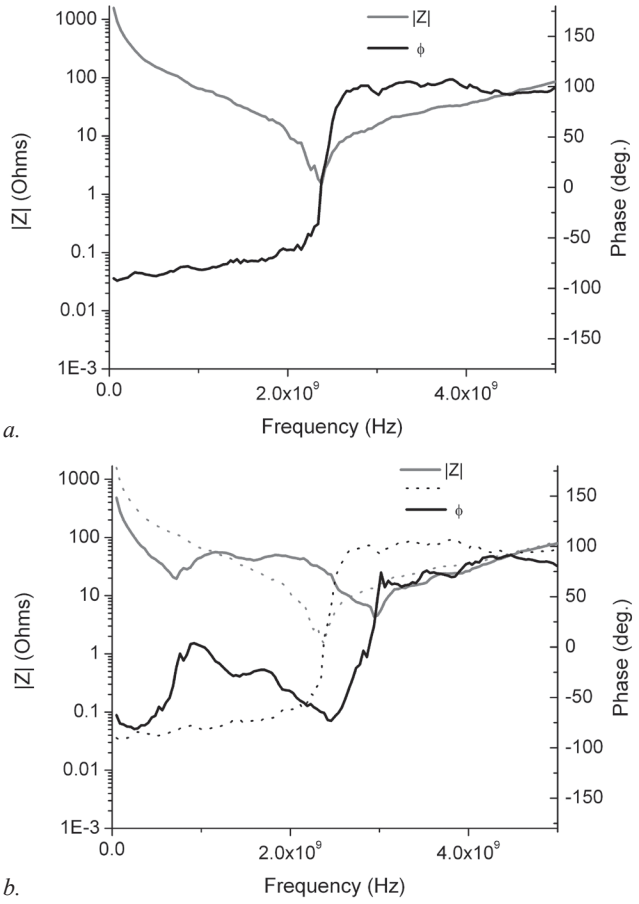


Figure 3: (a) A vacuum LC resonance indicated by a minimum in |Z| and a zero-crossing in the phase of Z. (b) The LC resonance shifted by the presence of an Argon plasma. Frequency shift indicates a plasma density of 3.8x10^{10} cm^{-3}. Axial magnetic field was 150 Gauss.

MEASURING PLASMA POTENTIAL AND EEDFS WITH RF FREQUENCY PROBES

When the network analyzer is operated in a frequency regime far removed from the plasma frequency resonance ($f << f_{pe}$) it can be used to measure the AC resistance of the plasma. If a variable DC bias is applied to the frequency probe this AC resistance measurement can be used to measure $(dI/dV)^{-1}$. This is expressed in Equation 4 below where R_{AC} is the AC resistance, C_{AC} is the AC capacitance I_e is the electron current V_{probe} is the DC probe bias and $\mathrm{Re}(Z_{AC}) = |Z|\cos(\varphi)$.

$$\mathrm{Re}(Z_{AC}) = \frac{R_{AC}}{1+\omega R_{AC} C_{AC}} \cong R_{AC} \cong \left(\frac{dI_e}{dV_{probe}}\right)^{-1} \tag{4}$$

As probe bias is varied the plasma potential, φ_{plasma}, is indicated by a minimum in R_{AC}. From the plasma potential the electron energy distribution function can be found using the technique outlined by Druyvesteyn [23]. Where $E = \varphi_{plama} - eV_{probe}$, m_e = electron mass, and A_p = probe area.

$$f(E) = \frac{4}{e^3 A}\sqrt{\frac{m_e E}{2}}\left(\frac{dR_{ac}^{-1}}{dV_{dc}}\right) \cong \frac{4}{e^3 A}\sqrt{\frac{m_e E}{2}}\left(\frac{d\,\mathrm{Re}(Z_{ac})^{-1}}{dV_{probe}}\right)\Bigg|_{V_{probe}=\varphi_p - E/e} \tag{5}$$

The application of this technique is shown in Figure 4 where both an RF Frequency probe and a Langmuir probe are used to measure the plasma potential and electron energy distribution function.

SUMMARY

RF frequency probes are able to perform density measurements in depositing plasmas and reactive gas plasmas where Langmuir probes are in-effective due to un-reliable charge collection. Furthermore RF frequency probes have proven to be a good alternative to Langmuir probes for measurements of n_e, electron energy distributions, and φ_{plasma} over a wide range of conditions. Complications to frequency probe density measurements in magnetic fields have been overcome using the LC Resonance Probe, which provides a local plasma density measurement and is un-affected by the presence of magnetic fields.

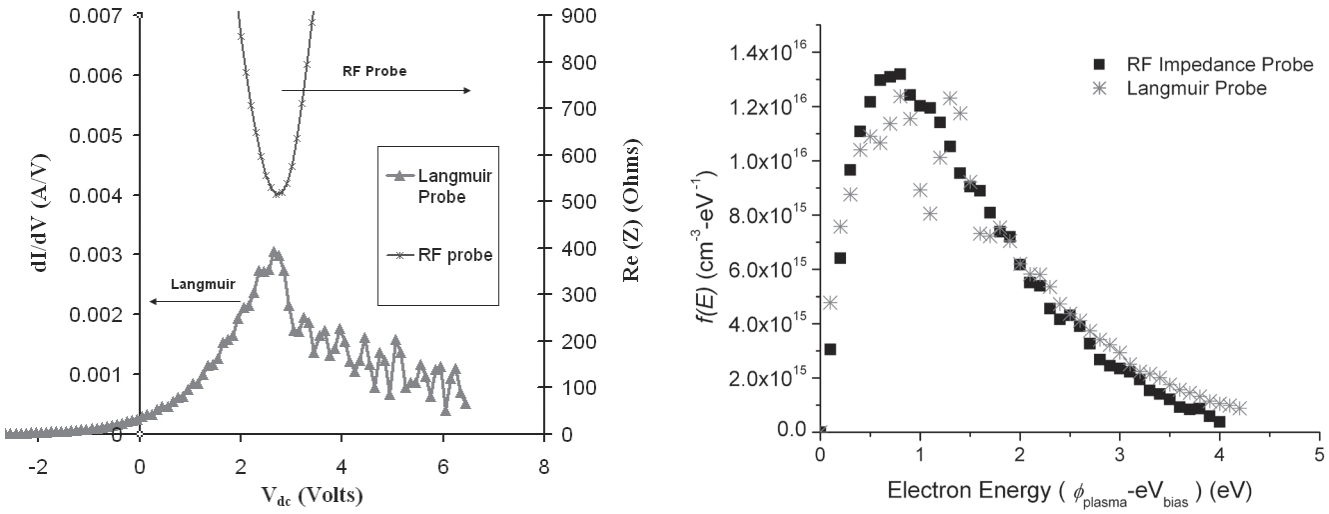


Figure 4: (a) R_{AC} as function of bias voltage illustrating the minimum at the plasma potential (2.5 V). Also the 1st derivative of a Langmuir probe trace showing the maximum at the plasma potential. (b) Applying equation (5) to the data in 3a, an EEDF for the plasma can be reconstructed showing good agreement between the RF probe and Langmuir probe.

REFERENCES

1. R.F. Fernsler, W.M. Manheimer, R.A. Meger, J. Mathew, D.P. Murphy, R.E. Pechacek, J.A. Gregor, "Production of large-area plasmas by electron beams" *Phys. Plasmas,* 5, 2137, 1998.

2. W.M. Manheimer, R.F. Fernsler, M. Lampe, R.A. Meger, "Theoretical overview of the large-area plasma processing system (LAPPS)" *Plasma Sources Sci. Technol.,* 9, 370, 2000.

3. D. Leonhardt, C. Muratore, S.G. Walton, D.D. Blackwell, R.F. Fernsler, R.A. Meger, "Generation of electron-beam produced plasmas and applications to surface modification" *Surf. Coat. Technol*., 682, 177– 178, 2004.

4. S. G. Walton, C. Muratore, D. Leonhardt, R.F. Fernsler, D.D. Blackwell, R.A. Meger, "Electron beam generated plasmas for materials processing" *Surf. Coat. Technol.*, 186, 40-46, 2004.

5. R. S. Harp and F. W. Crawford, "Characteristics of the Plasma Resonance Probe" *J. Appl. Phys.* 35, 3436, 1964.

6. F. W. Crawford, "Plasma Resonance Probe Characteristics in a Magnetic Field" *J. Appl. Phys.* 36, 3142, 1965.

7. T. Dote and T. Ichimiya, "Characteristics of Resonance Probes" *J. Appl. Phys*. 36, 1866, 1965.

8. H. Oya and T. Obayashi, "Measurement of Ionospheric Electron Density by a Gyro-plasma Probe: A Rocket Experiment by a New Impedance Probe" *Rep. Ionos. Space Res. Jpn.* 20, 199, 1966.

9. K. Balmain, "Impedance of a Spherical Probe in a Magnetoplasma" *IEEE Trans. Antennas Propag.* AP-14, 402, 1966.

10. J. Uramoto, "Measuring Method for Collision Frequency by a Radio Frequency Probe" *Phys. Fluids* 13, 657, 1970.

11. T. H. Y. Yeung and J. Sayers, "An R.F. Probe Technique for the Measurement of Plasma Electron Concentrations in the Presence of Negative Ions" *Proc. Phys. Soc. London*, Sect. B 70, 663, 1957.

12. K. Takayama, H. Ikegami, and S. Miyazaki, "Plasma Resonance in a Radio-Frequency Probe" *Phys. Rev. Lett.* 5, 238, 1960.

13. S. G. Bilen, J. M. Haas, F. S. Gulczinski, A. D. Gallimore, and J. N. Letoutchaia, "Resonance probe measurements of plasma densities in electric-propulsion plumes" *AIAA-99-2714, 35th Joint Propulsion Conference*, 1999.

14. H. Kokura, K. Nakamura, I. P. Ghanashev, and H. Sugai, "Plasma Absorption Probe for Measuring Electron Density in an Environment Soiled with Processing Plasmas" *Jpn. J. Appl. Phys*., Part 1 38, 5262, 1999.

15. Walker D N, Fernsler R F, Blackwell D D and Amatucci W E "Determining electron temperature for small spherical probes from network analyzer measurements of complex impedance" *Phys. Plasmas* 15 123506, 2008.

16. D. N. Walker, R. F. Fernsler, D. D. Blackwell, and W. E. Amatucci, *Phys. Plasmas*, 17, 113503, 2010.

17. D. R. Boris, R. F. Fernsler, S. G. Walton "A Comparative Study of DC Biased RF Impedance Probes and Langmuir Probes for the Measurement of Processing Plasma Parameters" *Plasma Sources Sci. Technol*. 21, 015011, 2012.

18. D. R. Boris, R. F. Fernsler, S. G. Walton, "The LC Resonance probe for determining local Plasma Density" *Plasma Sources Sci. Technol*. 20, 025003, 2011.

19. S.G. Walton, D. Leonhardt, D.D. Blackwell, R.F. Fernsler, D.P. Murphy, R.A. Meger, "Electron Beam Generated Plasmas for Materials Processing" *J. Vac. Sci. Technol*., A 19, 1325, 2001.

20. E. H. Lock, R. F. Fernsler, S. G. Walton "Experimental and theoretical evaluations of electron temperature in continuous electron beam generated plasmas" *Plasma Sources Sci. Technol*. 17, 025009, 2008.

21. D. N. Walker, R. F. Fernsler, D. D. Blackwell, W. E. Amatucci, and S. J. Messer "On collisionless energy absorption in plasmas: Theory and experiment in spherical geometry" *Phys. Plasmas*, 13, 032108, 2006.

22. D. D. Blackwell, D. N. Walker, and W. E. Amatucci "Measurement of absolute electron density with the plasma impedance probe" *Rev. Sci. Inst*., 76, 023503, 2005.

23. M. J. Druyvesteyn, *Z. Physik*, 64, 781, 1930.